A Rotatinag Mass Damper for Passive Seismic Control Of Rigid-Block Type Equipment above Isolated Floors

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Abstract

In recent years the issue of Performance-Based Seismic Design of structures (PBSD), is widely applied in the design methods. In PBSD, seismic levels and structural as well as non-structural performance are simultaneously considered. Seismic consequences such as human and financial losses are included in this design methodology. Equipment in service centers such as hospitals, power switching centers and control rooms have an important role for the function of these centers. Industrial machinery, electronics and instrumentation, as well as block-shaped equipment are among the important elements between equipment. Seismic isolation of the equipment has been shown effective for enhancing their performance and causing stability and reducing vulnerability during strong ground motions. An innovative isolation system including ball bearings and a rotating mass damper is introduced for this purpose. The idea was already proposed for buildings. The damper is composed of a horizontal rotating wheel attached to both the upper and lower isolation level. The generated force shows a negative stiffness in force-displacement diagram. The system dissipates energy by the inertia force generated by the rotating mass. The dynamic response of the rigid block equipment above the mentioned isolation system is numerically evaluated with a suite of seismic records. The results demonstrate a reasonable response of the isolation system comparing with the traditional installation methods.

Keywords: Block shape equipment, seismic isolation of equipment, rotating mass damper

1. Introduction

Seismic control methods are named as a major field in reducing the seismic response of structures. damages on non-structural components of buildings according to the level of investment has been performed on them (When compared to the level of investments, is greater than the percentage of total building system) have been significant. the mass of Secondary systems is less than the mass of other part of the main structure (floor, roof and walls, and pillars of buildings and industrial structures). These systems are not part of the structure's load-bearing components in an earthquake, but may be affected by large forces[2]. Rigid block equipment in many service providers such as hospitals, power switching centers and control rooms are used frequently. In this study a passive system is proposed which also will involve the performance of semi active systems. This system for seismic controlling of isolated floors of buildings will examine with a numerical method. The proposed system is called the rotational mass damper that located between the ground (or floor) and isolated floor. semi active mechanism for implementation the forces with the pseudo-negative equivalent stiffness, the passive performance of this damper, the potential of executivly, the possibility of its implementation and relatively low weight of block equipment, motivate us to do this study.

In prior studies, seismic analysis of secondary systems in two ways: time history analysis and spectral analysis has been done. Housner in 1963 evaluated the Dynamic response of equipment and rigid block that are located in rigid base under the of horizontal seismic stimulation. In that study, the acceleration of surface under the block Equipment (Basic acceleration) expressed as rectangular or sinusoidal pulses[3]. Markis and Roussos in 1998 examined rocking response of block equipment under sine and cosine pulse and for blocks with different aspect ratios after obtaining the equation of the motion for rocking in system and rocking response in the states of linear and nonlinear analysis and approximate solution, compared them with each other[4]. Yeong-Bin Yang, Hsiao-Hui Hung, Meng-Ju He in 2000, have examined the sliding and rocking response of rigid block on the ground, under the effect of horizontal acceleration of the earthquake in four modes: 1. stillness 2. Sliding 3. Rocking and slide together[16].

In addition to the methods that taken to seismic control of structural systems, some methods are used for the the seismic control of non-structural components's response and energy dissipation of the seismic isolated equipment. Among the extensive research that has been done in the field of seismic isolation of floors, can be noted in M.C.Constantinou, V Lambrou [5]. In their research, the numerical and experimental studies about isolation of computer centers that are contained block board, by using the fps system or systems with sliding friction surface, has been done. So that the system, in the case of non-isolated and isolated cases combined with three types of seismic isolation equipment and energy dissipation system tested and Were analyzed, and the responses are compared with each other in different scenarios. M.Hamidi, El Naggar in 2007 [6] studied the dynamic response of existing equipment on the isolated floor of a building with fixed base under harmonic and seismic loads. They used SCF systems or curved sliding system to isolate floors and check the Response of available system on the top floors of the structure. Chang-Jung Wang et al in 2014 [7] conducted Numerical and experimental studies on controlling seismic response of isolated equipment by using multi slippery system on inclined surface. Harvey et al in 2013[8] have done Numerical and experimental studies on isolated equipment made by slippery ball And assessed the effect of damping in the system on response of isolated equipments. Rotating mass damper used in this article by Pradono et al in 2008 [9] studied For the isolation of buildings. In this system, the idea has also been used as a negative stiffness. Imura and Prado in 2003 [10] using negative stiffness for controlling cable bridge. Their produced negative stiffness by a variable oil damper. Reinhorn et al in 2005 [11] and Vitti et al in 2006 [12] showed that the addition of a damper on structures at the same time reduces the acceleration, displacement and base shear. Imura in 2006 [13] Improved seismic behavior of structures by using negative stiffness ideas for structures with semi-active isolation. Imura and Prado in 2009 [14] used dampers with pseudo-negative stiffness for production of Hysteresis loop with negative stiffness. Sarlys and colleagues in 2011 [17] done theoretical and experimental studies about the idea of using innovative negative stiffness device that uses a pre-compressed spring in a frame. Pasala et al in 2011 [18] following the ideas of Sarlys et al presented new method for seismic protection by using the adaptive negative stiffness. Pasla et al in 2013 [19] continued their way with a three-story structure with elastic fixed support Experimentally and analytically. They [20] Also in 2015, put their attention on the three-story structures that yielded. Previous tests have been conducted on structures ranging from linear elastic.

2. Introduction the equipment for analyzing the seismic response

Most of the equipment inside the building with an acceptable approximation are block-shaped and their behavior is rigid Which is usually used in two ways inside buildings: inhibited and uninhibited equipment[4]. By seismic stimulation applied to the uninhibited block-shape equipment usually two types of response can be seen [1,2,4,15]: sliding or rocking. If the driving force input to the uninhibited block-shape equipment (In parallel with the contact area between the block and the surface of the substrate) overcome to the friction force between the contact surfaces and the underside of the block, blocks may begin to slide. Also, if the moment of the driving force exerted on the block, overcome the moment of resistant forces, the block will start rocking. In another case, the equipment may show both behavior of sliding and rocking simultaneously.

The rigid blocks is intended with dimensions B = 2 b and H = 2h and aspect ratio b / h where $\mathrm{R} = \sqrt{\mathrm{b}^2 + \mathrm{h}^2}$ and $\alpha = \tan^{-1}(\frac{b}{h})$ and R is distance between geometric and gravity center from rocking point of block, as shown in Figure 1.

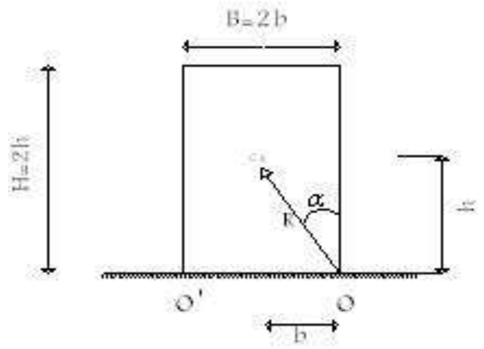


Fig.1- geometry of blocks

In this study, it was assumed that the above requirement has been established and the coefficient of friction between the block and its underside is high so that no slippage occurs on the block.

rigid block is considered under horizontal seismic excitation of the earthquake. In this case according to Figure (2-a) and (2-b), equation of motion for rocking a rigid block under effect of seismic excitation will be as follows [4,1,17,6,14] :

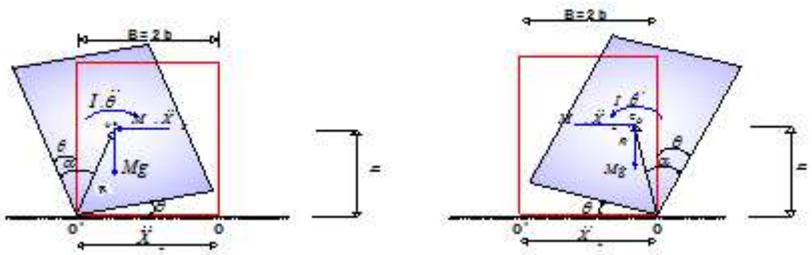


Fig.2- free Diagram of blocks under the effect of horizontal seismic excitation, a) θ <0, b) θ> 0

$$I = \frac{4MR^2}{3} \qquad , \qquad p = \sqrt{\frac{3g}{R}}$$

$$\ddot{\theta}(\mathrm{t}) = -p^2\left[\sin\left(\alpha sgn\big(\theta(t)\big) - \theta(t)\right) + \frac{\ddot{x}_g}{g}\cos\left(\alpha sgn\big(\theta(t)\big) - \theta(t)\right)\right] \tag{1}$$

In the above equation, unit of $p = \sqrt{\frac{3g}{R}}$ is rad/sec. R parameter is a measure of the size of the blocks. p is called the dynamic characteristics of the block equipments. Restore factor $r = \frac{\dot{\theta}_2^{\,2}}{\dot{\theta}_1^{\,2}}$, is for reducing the energy or energy dissipation by considering the impact between block and surface under it, Where $\dot{\theta}_1$ is rotational speed before impact to the underside and the $\dot{\theta}_2$ is angular velocity immediately after the impact.[1]

3. Rotating mass damper and a single degree of freedom system with it

pradono and colleagues in 2009, presented the idea of using the rotating mass damper as shown in figure 3 [9]. In the damper inner radius ri and outer radius re are shown in the figure .

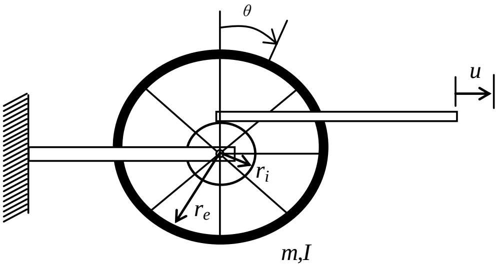


Fig.3- Schematic illustration of rotating mass damper

According to the results, dynamic relationship between the mass attached to a system of isolators with linear behavior and rotating mass dampers is derived as follows:

$$\left(1+\frac{\gamma}{\beta^2}\right)\ddot{u}+2\xi\omega\dot{u}+\omega^2u=-\ddot{u}_g \qquad (2)$$

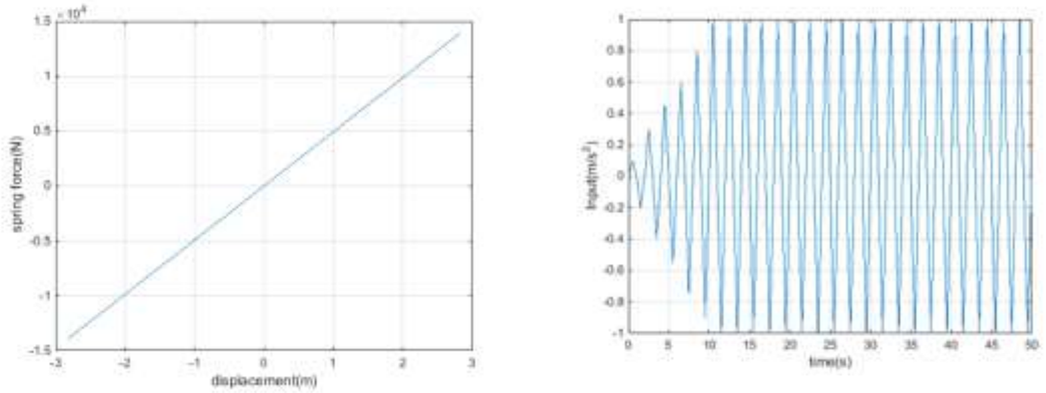
In this equation , $\beta = \frac{r_i}{r_e}$ and $\gamma = \frac{m}{M}$ and other parameters are shown in the figure. Suggested damper have ability to increase the natural period of system without reducing the stiffness of it.

4. Discussion the result

Response of model under harmonic load with a period equal to the period of the system in this study is provided (Resonance) with taking into account the different characteristics of the damper. In all these cases, the amount of viscous damping of system is intended equal zero (ξ =0).

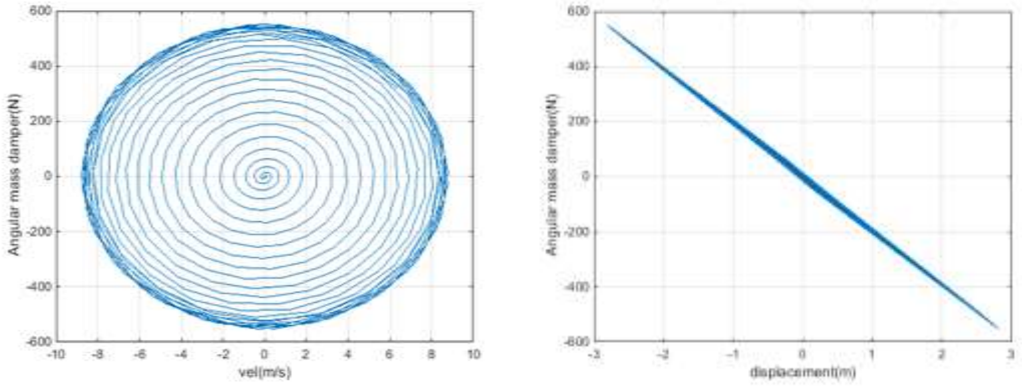
Table 1- Details of the system a degree of freedom used in the analysis

M(kg)	m(kg)	r_i(m)	r_e(m)	m_{eq}(kg)	β	γ	$T_P = 2\pi\sqrt{\frac{M}{K}}$	$T_s = 2\pi\sqrt{\frac{M+m_{eq}}{K}}$
500	5	0.3	0.6	20	0.5	0.01	2	2.0396



(b) (a)

Fig.4 - (a) input acceleration - (b) diagram of force-displacement of spring



(c) (d)

Fig.4- curve of (c) force – velocity of damper (d) force-displacement of damper

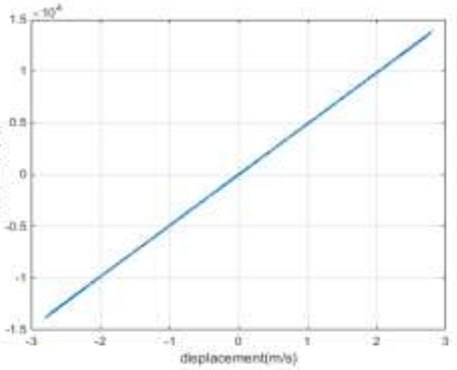


Fig.4 - (E) Base shear-displacement curve

Fig.4- Response of equipment and damper under harmonic load with T=2sec

As is clear from the above figures the diagram of the force-displacement of damper is a hysteresis loop with negative stiffness and also the area of this loop indicates the amount of energy discipation of the damper. Also, unlike the viscose damper with linear relationship between the damper force-velocity, about this damper the relationship between velocity and force of damper is

Elliptical. This process for the other proportions and characteristics of the damper is repeated in following table.

Table 2- propertices of sdof system with damper used for harmonic analysis

M(kg)	**m(kg)**	**r_i(m)**	**r_e(m)**	$m_{eq}(kg)$	**β=m/M**	$\gamma = \frac{\mathbf{ri}}{\mathbf{re}}$	$T_P = 2\pi\sqrt{\frac{M}{K}}$	$T_s = 2\pi\sqrt{\frac{M + m_{eq}}{K}}$
500	5	0.3	0.6	20	0.5	0.1	2	2.0396
250	5	0.3	0.6	20	0.5	0.02	2	2.0199
250	5	0.2	0.6	45	0.33	0.18	2	2.173

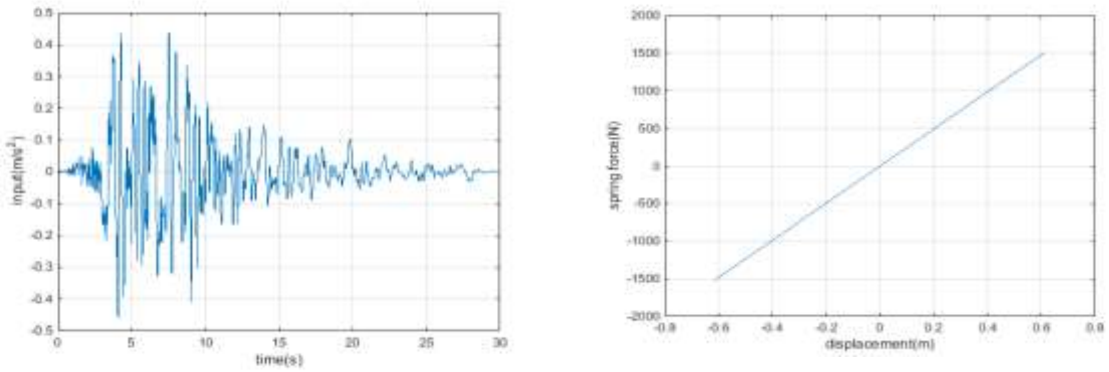
Table 3- Analysis sdof systems with the suggested damper employed under harmonic load

β=m/M	$\gamma = \frac{\mathbf{ri}}{\mathbf{re}}$	**Max(displacement)**	**Max(Acc)**	**Max(damper force)**	**Max(velocity)**
0.5	0.1	2.81	26.88	553.73	13984
0.5	0.02	1.61	14.88	313.7	40371
0.33	0.18	0.7	5.94	33.35	1790

In this part of the study to provide an estimate of the proposed damper energy discipation capability, analyzing the responses of similar system with viscose damper and calculating the viscose damping required to make the equal displacement, has been done. It has been compared to the two different modes: The first mode: γ= 0.02 and β= 0.5, the maximum absolute acceleration of the mass is 14/88m/s^2. And the second: γ =0.18 and β =0.33 which leads to absolute acceleration of approximately 94.5 m/s^2. The maximum displacement respectively for first and second modes is estimated 1/62 and 0.71 meters. Considering ξ =0.05, for a system of single degree of freedom with the mass of 250 kg and with the normal period of 2 seconds, the displacement is limited to about 0.7 meters, however, the acceleration is about 7.8 m/s^2. So the system with a rotating mass damper provides less absolute acceleration than the system with viscose damper.

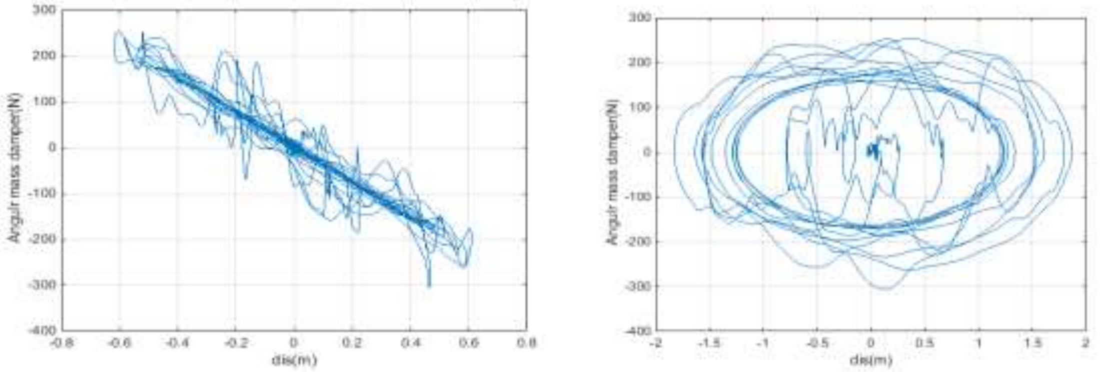
5. Comparison between responses of proposed system and viscose

In this section a system of single degree of freedom for time history analysis under earthquake record of Northridge -17645 Saticoy st that took place in 1994, with the proposed rotating mass damper with γ =0.18 and β =0.33 evaluated and the results are depicted in the following charts:



(a) (b)

Fig.5- (a)input acceleration (b)force-displacement curve of spring



(c) (d)

Fig.5- curve of (d): damper force- velocity (c) damper force- displacement

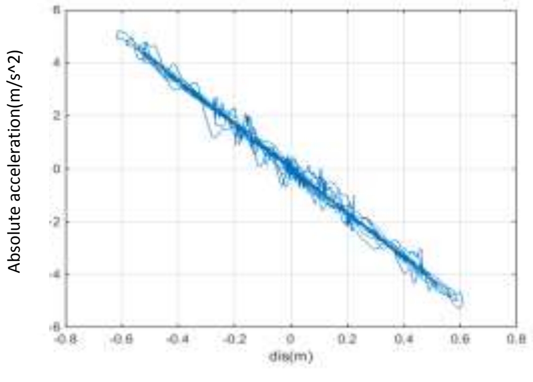
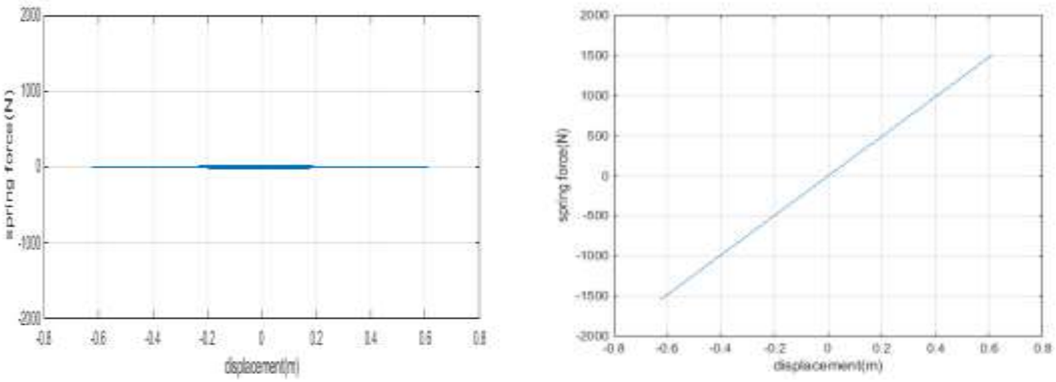


Fig.5-(e) the absolute acceleration- displacement curve

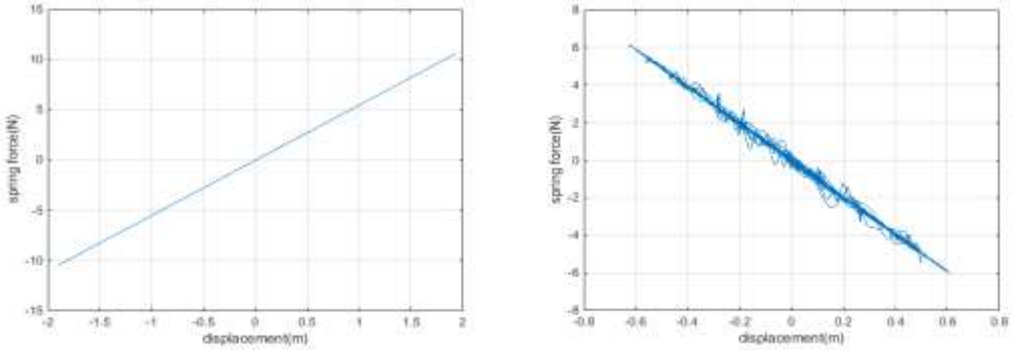
Fig.5-response of equipment with T=2 and damper under the Northridge 1994

Then obtained response of system with viscose damper that displacement of it is equal to displacement caused by rotational damper under the Northridge - 17645 Saticoy St:



(b) (a)

Figure 6. (a) force-displacement of spring (b) viscose damper force- displacement curve



(d) (c)

Fig.6-(c) absolute acceleration-displacement curve(d) viscose damper force-velocity

Fig.6- response of system whit T=2 and viscous damper under Northridge - 17645 Saticoy St

As is clear from the figures the curve of viscose damper force-displacement is a hysteresis loop with positive stiffness and the relationship between the damping force-velocity is linear and equal to a constant value. According to the above analysis the system with viscose damper respect to the rotating mass damper, reduced the maximum displacement and maximum damper force, but the absolute acceleration in the system of a single degree of freedom is increased.

6. Rocking of block on the isolated floor with rotating mass damper

As mentioned in the first of article, in this project assume that the friction of isolated floor capable to prevent sliding of block. After obtaining responses of isolated floor with rotating mass damper, entered floor absolute acceleration to block with dimension of 0.3*1 meters, and obtain rocking response of it with the effect of reduced-energy under impact between the block and the isolated floor. The results of the analysis of system under Northridge - 17645 Saticoy in 1994 shows that the assumed block will rock and increasing in its rotation angle is specified in the following diagram.

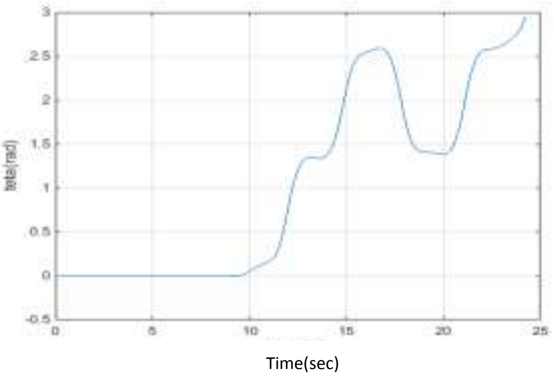


Fig.7- response of block with b/h = 0/3 under 1994 Northridge - 17645 Saticoy St

7. Conclusion

In this paper we investigate the use of a rotating mass damper system with the isolated floor in reducing the displacement and absolute acceleration of a sdof system, finally, rocking response of block with suggested damper obtained. isolation system used in this study had a noticeable impact in reducing the rocking response of block. The choice of base isolation system to provide the displacement and period of vibration due to low weight of isolated equipment is necessary and has specific design problems.

8. Refrences

[1]. Afshin. Kalantari, v.shahbazi , "effect of seismic isolation on fragility curve of nonstructural components, journal of sharif university, 2009

[2]. T.T.Soong and D.Lopez Garcia, "Seismic Vulnerability and Protection of Non-structural Component", *Joint NCREE/JRC Workshop International Collaboration on Earthquake Disaster Mitigation Research*, 73-82, National Center,2003

[3]. George W. Housner, "The Behavior of Inverted Pendulum Structures During Earthquakes", *Bolletin of the Seismological Society of America*, Vol. 53, No. 2, pp. 403-417, 1963.

[4]. Yeong-Bin Yang & Hsiao-Hui Hung, Meng-Ju He, "Sliding and Rocking Response of Rigid Blocks Due to Horizontal Excitations", *Structural Engineering and Mechanics*, Vol. 9, No. 1 (2000), 1-16.

[5]. V. Lambrou, M.C. Constantinou, " Study of Seismic Isolation Systems for Computer Floor" , *NCEER-94-0020 , 7/19/1994*.

[6]. M. Hamidi and M. H. El Naggar,' On the performance of SCF in seismic isolation of the interior equipment of buildings', *Earthquake Engng Struct. Dyn*. 2007; 36:1581–1604.

[7]. Shiang-Jung Wang1, Jenn-Shin Hwang, Kuo-Chun Chang, Chia-Yi Shiau1,Wang-Chuen Lin1, Mu-Sen Tsai, Jia-Xiang Hong and Yin-Han Yang, " Sloped multi-roller isolation devices for seismic protection of equipment and facilities ", *Earthquake Engng Struct. Dyn*. 2014; 43:1443–1461.

[8]. P. Scott Harvey Jr., Gérard-Philippe Zéhil and Henri P. Gavin, " Experimental validation of a simplified isolation systems", *Earthquake Engng Struct. Dyn*. 2014; 43:1067–1088. model for rolling

[9]. Mulyo Harris Pradono,y,z, Hirokazu Iemura, Akira Igarashi,and Afshin Kalantari, " Application of angular-mass dampers to base-isolated benchmark buildingStruct". *Control Health Monit*. 2008; 15:737–745.

[10]. H.Iemura and M.H.Pradono, "Application of pseudo-negative stiffness control to the benchmark cable-stayed bridge*", J.Struct. Control*, vol. 10, no.3-4, pp.187-203 , Jun.2003.

[11]. A. M. Reinhorn, S.Viti and G. Cimellaro, " Retrofit of structures: Strength Reduction and Damping Enhancement ",in 37th *Technical Panel Meeting on Wind and Seismic Effects*,2005.

[12].S. Viti, G.P.Cimellaro, and A.M. Reinhorn , "Retrofit of a hospital through strength reduction and enhanced damping", *Smart Struct.* Syst., vol. 2, no.4, pp.339-355, 2006.

[13].H.Iemura, A. Igarashi, M. H.Pradono, and A.kalantari, "Negative stiffness friction damping for seismically isolated structures*", Struct. Control Heal. Monit*., vol. 13, no. 2-3, pp.775-791, Mar. 2006.

[14]. H.Iemura, M. H.Pradono, "Advances in the development of pseudo-negative stiffness dampers for seismic response control", *Struct. Control Heal.Monit.,*p.n/a,2009.

[15]. D. Lopez Garcia and T. T. Soong, "Sliding Fragility of Block-Type Non-structural Components, Part-1: Unrestrained Components", *Earthquake Engineering and Structural Dynamics*,2003; 32:111-129.

[16]. Nicos Makris & Yiannis Roussos, "Rocking Response and Overturning of Equipments under Horizontal Excitation", *Report PEER-University of Berkeley*. 1998/05.

[17]. A. A. Sarlis, D. T. R. Pasala, M. C. Constantinou, A. M . Reinhorn, S. Nagarajaiah, and D. P. Taylor, "Negative Stiffness Device for Seismic Protection of Structures", *Journal of Structural Engineering*. P 468, 2012.

[18].D. T. R. Pasala, a. a. Sarlis, S. Nagarajaiah, A. M. Reinhorn, M. C. Constantinou, and D. P. Taylor, "A New Structural Modification Approach for Seismic Protection Based on Adaptive Negative Stiffness Device: Conceptual Analysis (asce*)", in stuructures congress*, 2011, pp.2892-2904.

[19].D. T. R. Pasala, a. a. Sarlis, S. Nagarajaiah, A. M. Reinhorn, M. C. Constantinou, and D. P. Taylor, "Adaptive Negative Stiffness: New Structural Modification Approach for Seismic Protection", *J. Srruct. Eng*., vol. 139, no. 7,pp. 1112-1123, Jul.2013.

[20].D. T. R. Pasala, a. a. Sarlis, S. Nagarajaiah, A. M. Reinhorn, M. C. Constantinou, and D. P. Taylor, "Apparent Weakening in Sdof Yielding Structures Using a Negative Stiffness Device: Experimental and Analytical Study", *J. Srruct. Eng*., vol. 141, no. 4,p. 04014130, Apr. 2015